Spatiotemporal Variability of Precipitation and Soil Moisture in WGEW

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1. Introduction

Precipitation and soil moisture characteristics in WGEW [centered at (31° 43' N, 110° 41' W)] during the North American Monsoon are presented by utilizing 56 (10) years of 1 July – 30 September precipitation (soil moisture) data from 88 gauges (19 probes). In order to increase soil moisture measurement density and temporal coverage, a water balance model is developed to produce soil moisture at all 88 gauge sites using solely precipitation as input and calibrated using 19 soil moisture probes. Globally and regionally, observation coverage is far more sparse, and the densely instrumented WGEW network gives us an opportunity to study how much coverage is actually necessary to accurately represent precipitation and soil moisture on daily and monthly timescales.

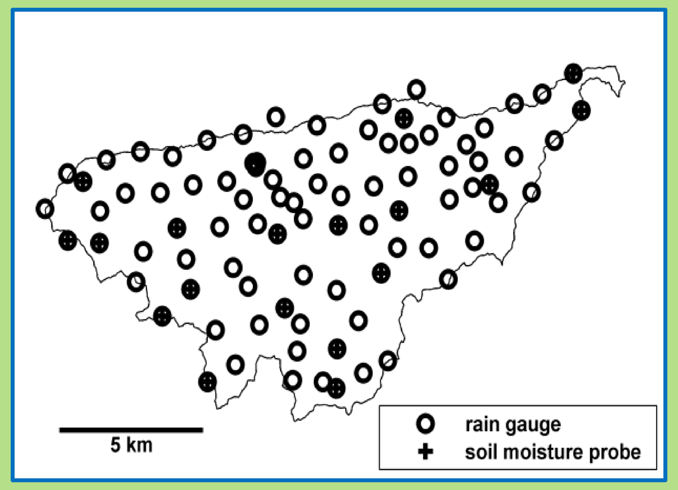

Figure 1: Location of the 88 current rain gauges and 19 soil moisture probes in WGEW.

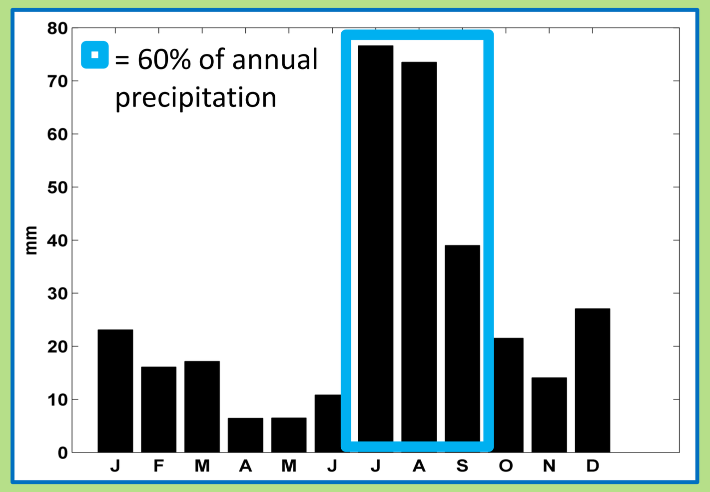

Figure 2: Spatially averaged monthly precipitation totals in WGEW.

2. Soil Moisture Model

Modeling surface soil moisture (θ) generally requires large amounts of knowledge of atmospheric conditions and soil properties so estimating soil moisture solely from precipitation is usually inaccurate. However, by assuming certain conditions (i.e. maximum evapotansipration) to be essentially constant during this 3 month period and calibrating the model so that it fits the in situ data best (Table 1), we can produce daily time series of θ that agree well with observations at a depth of 5 mm. Quality testing of the in situ data is performed first to ensure that the model is calibrated to "good" data.

$$\underbrace{\theta_t = \theta_{t-1}}_{a} + \frac{\Delta T}{Z}\left[\underbrace{(1-B^4)*\min(p_t - I, p_{crit})}_{b} - \underbrace{EA^{\beta}}_{c} - \underbrace{a_1 A^{a_2}}_{d}\right]$$

$$A = \frac{\theta_{t-1} - \theta_w}{\theta_{th} - \theta_w} \quad 0 \le A \le 1$$

$$B = \frac{\theta_{t-1}}{\theta_s} \quad 0 \le B \le 1$$

$$I = \min(I_m, p_t)$$

ΔT	0.5 hr	θ_{th}	0.28 m^3 m^{-3}
E_{max}	0.34 mm hr^{-1}	β	1.4
I_m	0.3 mm hr^{-1}	a_1	0.3 mm hr^{-1}
p_{crit}	40 mm hr^{-1}	a_2	2
θ_s	0.35 m^3 m^{-3}	Z	75 mm

Table 1: calibrated model parameter values

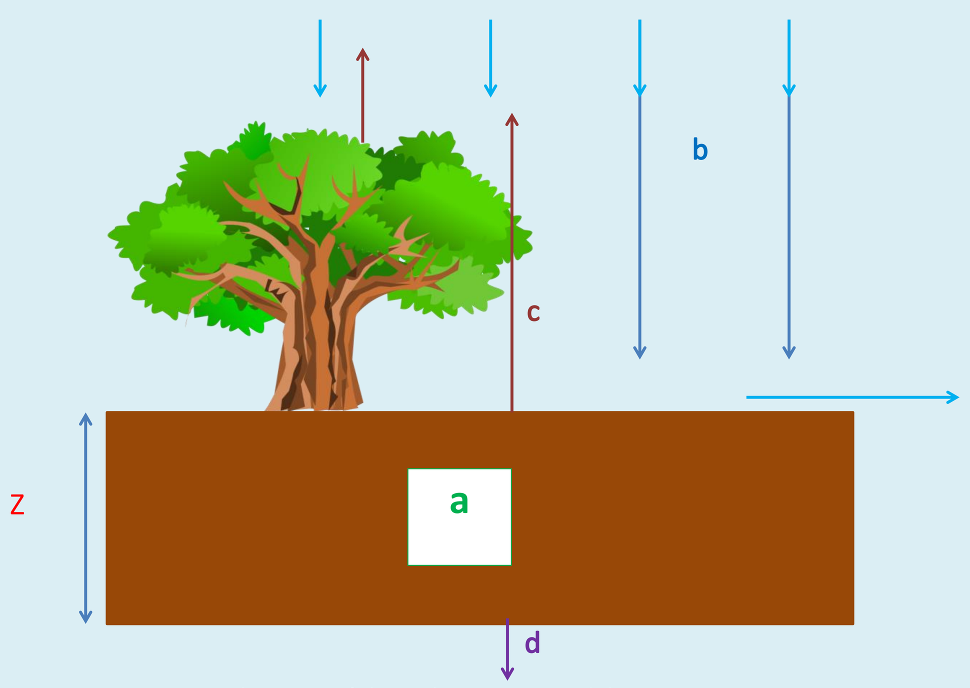

Figure 3: Schematic of the soil moisture model

The quality of the resulting θ is assessed by the correlation (R) and root mean square deviation (RMSD) at each gauge with a co-located θ probe of the daily time series produced at each gauge with its co-located in situ time series (Fig. 4, Table 2).

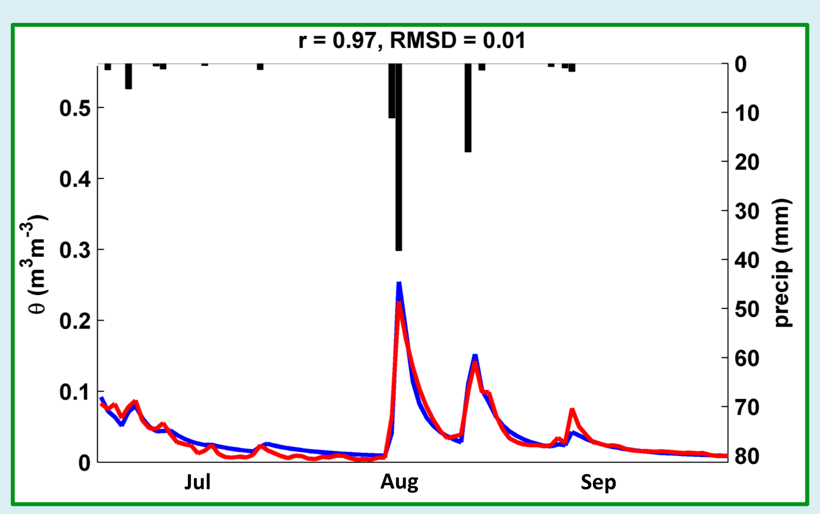

Figure 4: Comparison of daily in situ (red) and co-located modeled (blue) θ with precipitation (black) at a gauge in 2009.

Model vs. In situ	
R	0.89
RMSD	0.033 m^{3}m^{-3}

Table 2: Average correlation and RMSD of modeled daily soil moisture at each gauge compared with co-located in situ soil moisture.

Percent of Precipitation	
	Mean (%)
$\Delta\theta$ (a)	-0.1
Runoff (b)	9.8
Intercepted (b)	7.1
ET (c)	24.1
Drainage (d)	59.1

Table 3: Average percentage of summer precipitation that each term accounts for in the model.

3. Trend Analysis

With over 5 decades of precipitation and soil moisture measurements, it is possible to perform trend analyses. While there is a general agreement that total precipitation is not significantly increasing or decreasing in this region, it has been suggested that there is a possible increase in intensity of individual events and a decrease in event frequency (fraction of 30-minute time steps with any rainfall).

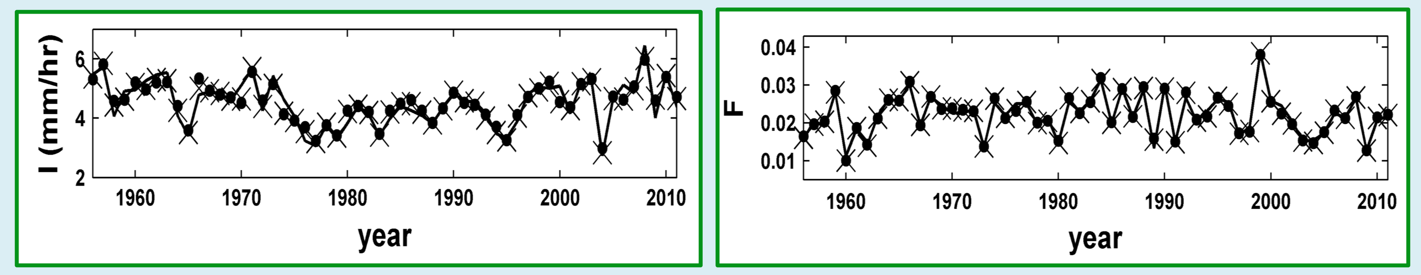

Figure 5: July 1 – September 30 spatial mean (circle), median (x), and maximum likelihood (line) values (found temporally at each grid cell and averaged spatially) of precipitation intensity (left) and frequency (right).

Intensity		
	1956-1999	1956-2011
Trend (mm/hr/dec)	-0.3	-0.03
P-value	0.13	0.91

Frequency		
	1956-1999	1956-2011
Trend (/dec)	+1.03E-3	4.6E-5
P-value	1.8E-4	0.59

Table 4: Trends in precipitation intensity and frequency for an intermediate period (1956-1999) and the full 56 years (1956-2011)

No long-term trends are found in precipitation intensity or frequency (or precipitation total and summer average θ) (Fig. 5, Table 4). However, intermediate trends influenced our analysis of possible multi-decadal patterns (section 4).

4. Multidecadal Patterns

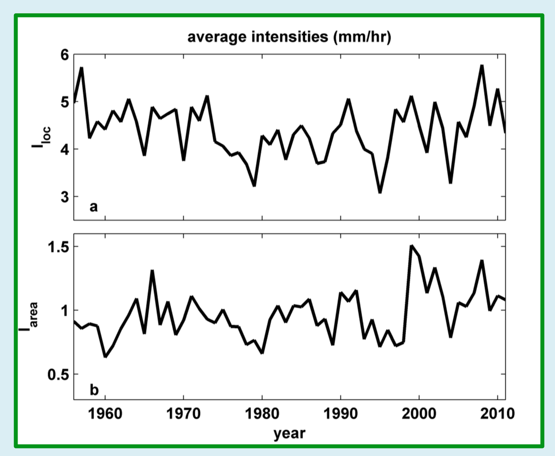

Figure 6: Spatial average Jul-Sep intensities at all gauge sites (I_{loc}) in (a), and of intensity of spatially averaged 30 min precipitation (I_{area}) in Jul-Sep in (b).

Storm intensity can be calculated in two ways: averaging the individual gauge intensities for all gauges with any precipitation (I_{loc}), and averaging the amount of precipitation at all gauges for each time step during which there is precipitation and taking the average (I_{area}) (Fig. 6). Clearly, if the storms cover only a few gauges, I_{area} will be small while I_{loc} may be large.

Storm coverage is defined as average percent of WGEW area that received rainfall during any time steps during which any rain fell. A pronounced peak in storm coverage is observed in the late 1970's (Fig. 7).

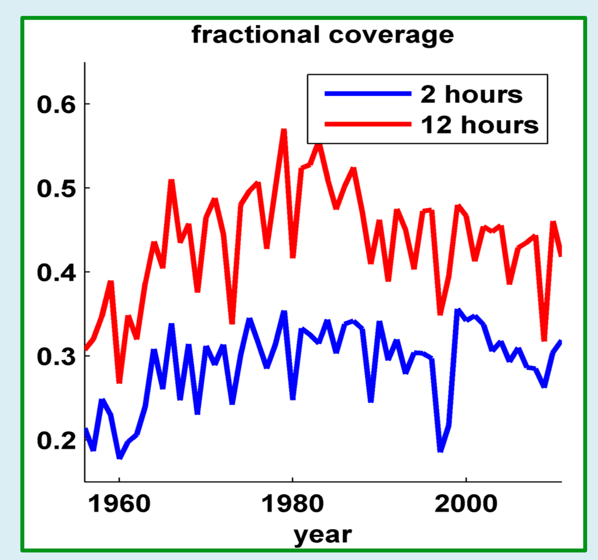

Figure 7: Average storm coverage for 2 and 12 hour time steps in each year.

	PDO	AMO
T	-0.09	-0.13
I	-0.46	0.18
F	0.16	-0.25
C (12 h)	0.32	-0.38

■ = significant at the 0.01 level

Table 5: Correlations of precipitation total (T), intensity (I), frequency (F), and 12-hour storm coverage (C) with PDO and AMO.

This multidecadal pattern is related to the Pacific Decadal Oscillation (PDO) and Atlantic Multidecadal Oscillation (AMO), which are known modes of climate variability related to sea surface temperature anomalies (Table 5).

References

Stillman, S., X. Zeng, W. J. Shuttleworth, D. C. Goodrich, C. L. Unkrich, M. Zreda, 2013: Spatiotemporal Variability of Summer Precipitation in Southeastern Arizona. *J. Hydrometeor*. In press.

Stillman, S., J. Ninneman X. Zeng, T. Franz, R. L. Scott, W. J. Shuttleworth, K. Cummins: Summer Soil Moisture Spatiotemporal Variability in Southeastern Arizona (submitted)

5. Spatiotemporal Variability

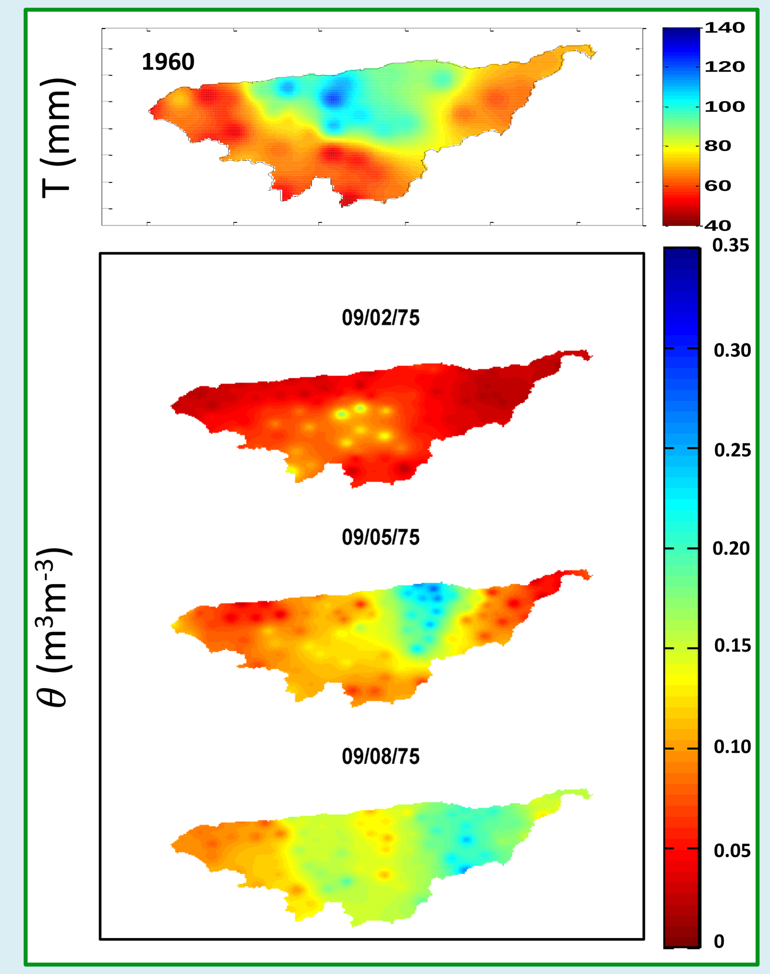

Figure 8: Spatial distribution of precipitation totals in 1960 (top) and daily average soil moisture before and after rain events in September, 1975.

Precipitation can have relatively large spatial variability even for the total from 1 July – 30 September (Fig. 8). In general, only 8 gauges are required to estimate spatial average total precipitation with 10% uncertainty in the 30 day average, but even 25 gauges would only give 50% relative uncertainty in daily average. On the other hand, spatially averaged θ can generally be estimated to a high degree of accuracy on even a daily timescale with just a few samples. However, a loss of variability is seen when just a few samples are used (Fig. 8, 9). For example, the spatial range (highest minus lowest gridded value) of daily θ is up to 0.22 m^{3}m^{-3} higher when using 88 samples versus 19. The spatial range on a given day is as large as 0.31 m^{3}m^{-3}, which is nearly the full possible range of values.

Even from year to year, there is large variability in spatially averaged total precipitation and average soil moisture. Spatially averaged summer precipitation totals vary from 93.6 – 325.8 mm. Average θ varies from 0.048 – 0.090 m^{3}m^{-3}.

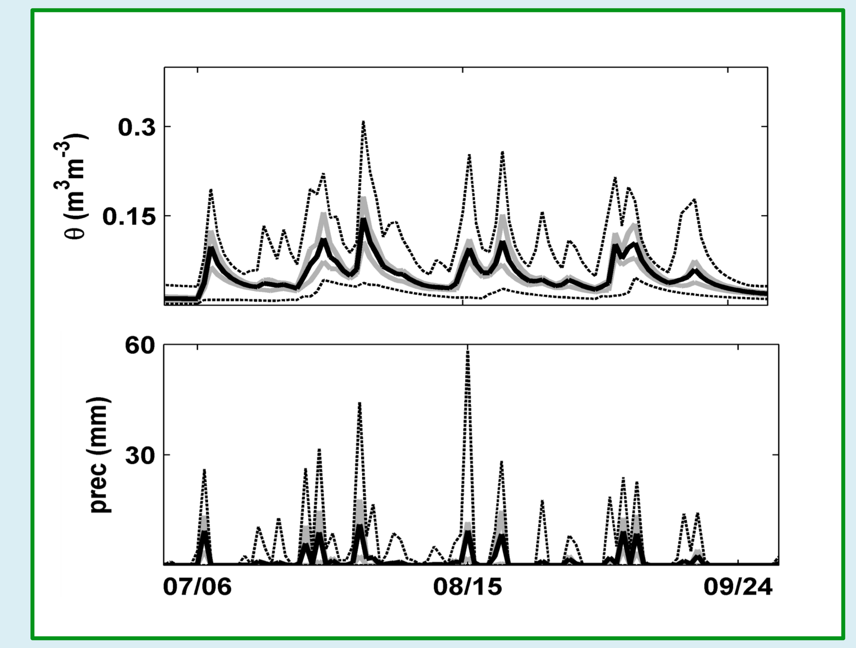

Figure 9: Daily mean, IQR, and range of θ (top) and precipitation (bottom) in 1960

θ has significantly lower daily spatial variability than that of precipitation. One way this can be seen is by the correlation of precipitation (θ) with all of the other gauges (probes) versus the distance between them (Fig. 10).

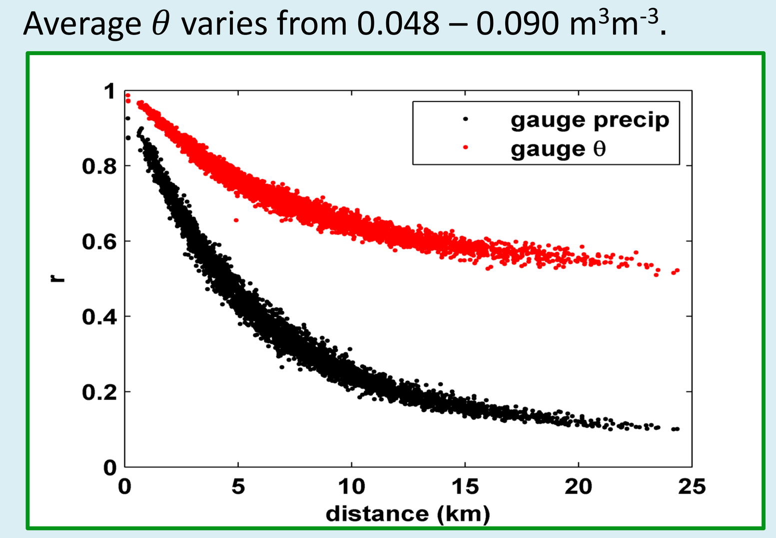

Figure 10: Correlation at each gauge versus distance of daily precipitation (black) and soil moisture (red)

Soil moisture has a "memory" of past precipitation events. The scale of this "memory" is explored by comparing the e-folding timescales of precipitation and soil moisture. This is found by fitting the autocorrelation to $e^{-t/T}$ where t is the lag and T is the timescale (Fig. 11). On average, precipitation has a timescale of 1.8 days and 5 cm θ has a timescale of 5.7 days.

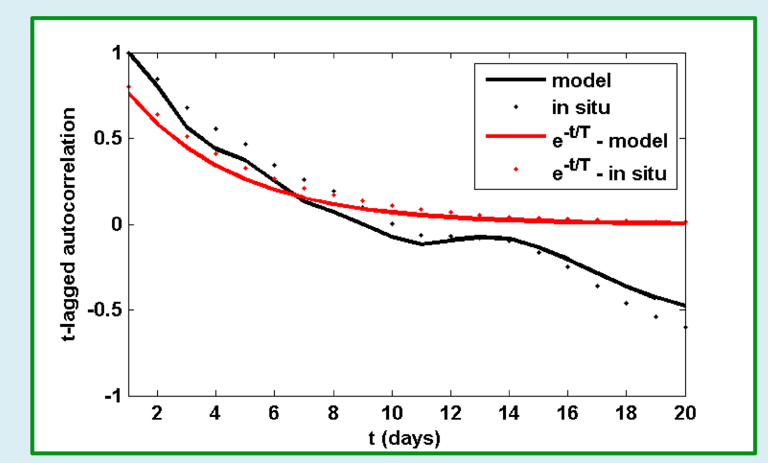

Figure 11: Autocorrelation of all gauge (black line) and all in situ (black circle) versus lag, t (in days) and best fit $e^{-t/T}$ for all gauge (red line) and all in situ (red circle) in 2003.

6. Conclusions

1. A gauge-based soil moisture model extends the measurement period from 10 – 56 years and increases the number of measurements from 19 – 88 locations.
2. Trends in frequency and intensity of precipitation suggested in previous work are not found to exist over WGEW from 1956 – 2011. There are also no trends found in soil moisture.
3. Significant correlation (p<0.01) is found between PDO and precipitation intensity and storm spatial coverage and between AMO and storm coverage.
4. Soil moisture has lower spatial variability than precipitation
   a. 8 gauges are necessary to estimate spatially averaged monthly precipitation in this region during the summer months. Daily precipitation requires many more gauges.
   b. Daily soil moisture can be estimated with the current in situ network (19 probes) but there is a loss of information on spatial variability.
5. Soil moisture has longer temporal memory than precipitation with an average e-folding timescale of 5.7 days in comparison with 1.8 days for precipitation.